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This progress report covers the period from January, 1993 to January, 1994. First, we list the papers published during the period. Next, we list the papers submitted for publication and the papers presented at scientific meetings. The personnel are then listed, and, finally, we conclude with a brief discussion of the problem areas in which future research efforts will be concentrated. We feel that more research should be devoted to this topic. Not only is this research needed to understand the basic stimulus variables in more detail, but it is needed in order to apply this research to real-world situations. In most realistic situations, the change in the auditory spectrum occurs at different times and with different degrees of synchrony among the components of the complex.

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Complex Auditory Signals
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This progress report covers the period from January, 1993 to January, 1994. First, we list the papers published during the period. Next, we list the papers submitted for publication and the papers presented at scientific meetings. The personnel are then listed, and, finally, we conclude with a brief discussion of the problem areas in which future research efforts will be concentrated.

Published Papers (all 1993).

1) Eddins, David A., Amplitude modulation detection of narrow-band noise: Effects of absolute bandwidth and frequency region. Journal of the Acoustical Society of America, **93**, 470-479.

2) Dai, Huanping and Green, David M., Discrimination of spectral shape as a function of stimulus duration. Journal of the Acoustical Society of America, **93**, 957-965.

3) Zera, Jan and Green, David M., Detecting temporal onset and offset asynchrony in multicomponent complexes. Journal of the Acoustical Society of America, **93**, 1038-1952.

4) Zera, Jan and Green, David M., Detecting temporal asynchrony with asynchronous standards. Journal of the Acoustical Society of America, **93**, 1571-1579.

5) Zera, Jan, Onsan, Zekiye A., Nguyen, Quang T. and Green, David M., Auditory profile analysis of harmonic signals. Journal of the Acoustical Society of America, **93**, 3431-3441.

6) Zera, Jan and Green, David M., Temporal asynchrony of less than one-half cycle can be detected in harmonic complexes. Journal of the Acoustical Society of America, **93**, 3514-3515.

7) Kidd, Gerald, Jr. and Dai, Huanping, A composite randomization procedure for measuring spectral shape discrimination. Journal of the Acoustical Society of America, **94**, 1275-1280.

Chapters in books to appear in 1993.

8) Green, David M., Auditory intensity discrimination. In Fay, Richard R. and Popper, Arthur N., Editors, Volume 3 of the Springer Series in Auditory Research: Human Psychophysics, Springer-Verlag, New York, 1993.

9) Eddins, David A. and Green, David M., Temporal integration and temporal resolution. In Moore, Brian, Editor, "Hearing" for

the *Handbook of Perception and Cognition*, Cambridge University, London, 1993.

Submitted for publication and under review.

10) Lee, Jungmee, Amplitude modulation rate discrimination with sinusoidal carriers. *Journal of the Acoustical Society of America*.

11) Lee, Jungmee and Green, David M., Detection of mistuning of a partial in a harmonic complex. *Journal of the Acoustical Society of America*.

12) Gu, Xiang and Green, David M., Further studies of a maximum-likelihood yes-no procedure. *Journal of the Acoustical Society of America*.

13) Eddins, David A. and Wright, Beverly A., Comodulation masking release for single and multiple rates of envelope fluctuation. *Journal of the Acoustical Society of America*.

14) Middlebrooks, John C., Clock, Ann, Xu, Li and Green, David M., A panoramic code for sound location by cortical neurons. *Science*.

15) Gu, Xiang, Wright, Beverly A., and Green, David M., Letter to the Editor, Failure to hear binaural beats below threshold. *Journal of the Acoustical Society of America*.

16) Zhou, Bin and Green, David M., Effect of standing waves on high-frequency threshold. *Journal of the Acoustical Society of America*.

Papers presented at scientific meetings.

50th Anniversary of the Parmly Hearing Institute, Loyola University, Chicago, IL.

Green, David M., Psychoacoustics and Auditory Perception, 1993.

AFOSR Review Research In Hearing, Fairborn, Ohio.

Green, David M., Complex Auditory Signals, 1993.

Association for Research in Otolaryngology, St. Petersburg Beach, Florida, February 7-11, 1993.

Green, David M., A maximum likelihood procedure for estimating threshold in a yes-no task.

Wright, Beverly A. and Dai, Huanping, The detectability of unattended signals in overshoot conditions.

Dai, Huanping, Nguyen, Quang and Green, David M., Spectral-shape discrimination as a function of the number of spectral components at three stimulus durations.

Acoustical Society of America, Ottawa, Canada, May 17-21, 1993.

Green, David M., Detecting changes in spectral shape of complex auditory signals: Profile analysis.

Eddins, David A. and Wright, Beverly A., Comodulation masking release for AM noise maskers.

Green, David M., A threshold estimate in a yes-no task using a maximum likelihood procedure.

Sorkin, Robert D. and Dai, Huanping, Psychoacoustic models of group signal detection.

Wright, Beverly A., and Dai, Huanping, Detection of unexpected tones in noise: The effect of signal duration.

Zera, Jan and Green, David M., Detecting asynchrony of a single component with synchronous and asynchronous standards.

Dai, Huanping, Decision rules in spectral-shape discrimination with and without signal uncertainty.

Personnel.

David M. Green, Graduate Research Professor. Dr. Green has been notified that he will be presented the Gold Medal of the Acoustical Society of America at the Boston meeting in June.

Huanping Dai, Asst. Research Scientist. Dr. Dai received his doctoral degree from Northeastern University in 1989. He received a Shannon Award (NIH) in 1993. Dr. Dai has been awarded a five-year NIH FIRST award.

Beverly A. Wright, NIH Post Doctoral Fellow. Dr. Wright received her doctoral degree from the University of Texas in 1990.

Kourosh Saberi, NIH Post Doctoral Fellow. Dr. Saberi received his doctoral degree from the University of California at Berkeley in 1993.

David A. Eddins, Post Doctoral Fellow. Dr. Eddins received his doctoral degree from the University of Florida in 1993.

Jan Zera, Fulbright fellow, 1991-93. Dr. Zera has joined the National Research Council in Ottawa Canada.

Bin Zhou, Graduate Student, expected to graduate 1994.
Xiang Gu, Graduate Student, terminal M. A. expected 1994.
Jungmee Lee, Graduate Student, expected to graduate 1994.

Progress Report.

I will not attempt to review each of the published or submitted papers. The abstracts of the papers present the best summaries of these research efforts. Three areas do deserve special discussion. The first is a letter-to-the-editor concerning the audibility of binaural beats. It fails to replicate an older study by Groen (1964), which, in our opinion, has been seriously overinterpreted in secondary sources. The other two because they will undoubtedly become the focus of future research efforts.

Binaural Beats.

Groen (1964, Acta Oto-Laryngol. 57, p. 224-230) reported that binaural beats could be heard when the level of the stimulus at one of the two ears was 10-25 dB below threshold. Although this result was never replicated, it has been widely cited in the literature. Clearly, the detection of binaural beats must depend on the neural interaction between the two ears. Binaural beats can only be heard at low frequencies where phase-locking is possible. The most probable detection mechanism is a change in phase-locking of these low-frequency auditory fibers. As Pickles (p. 257) puts it--Groen's results suggest "that phase information could be transmitted by the auditory nerve when the stimulus was below threshold, and has the corollary that phase information did not by itself determine the absolute threshold." It is odd that phase-locking is not involved in determining absolute threshold, because, in animal studies, a change in phase-locking is the first evidence of the presence of a weak sinusoidal signal. Often changes in phase-locking occur 10-20 dB below levels where changes in overall rate of firing are evident (Rose, Brugge, Anderson, and Hind, 1967, J. of Neurophysiology 30, p.769-793.)

Gu, Wright, and Green (see reference 15 above) have recently replicated Groen's results. They obtained psychometric functions for both absolute threshold and for the detection of binaural beats in a two-alternative forced-choice test. Special controls were used to prevent the creation of artifactual pitch cues caused by changing the frequency of one of the tones to produce the binaural beats. One of the sinusoids was fixed at a clearly audible level--

about 20-dB sensation level. The other sinusoid was adjusted in level to determine when binaural beats could be heard. The result obtained with six listeners was that there was no measurable difference between the detectability of the binaural beats and the audibility of the weaker sinusoid. We were not able to suggest any reason for the discrepancy between Groen's results and ours.

We hope that this discrepancy will stimulate other investigators to measure the audibility of binaural beats.

High-Frequency Thresholds and Profile Analysis.

The fourth-year graduate student, Zhou Bin, has been working on a system for estimating absolute thresholds at high frequencies. The problem is that above about 6000 Hz sizable standing waves occur in the ear canal, and there is no simple relation between the pressure measured at the entrance of the ear canal and the pressure on the ear drum. Mr. Bin has developed several procedures to estimate the ear drum pressure. He finds correlations between this predicted pressure and measured absolute thresholds of over 0.9. He also has developed a long lossy tube that effectively eliminates standing waves. We have used this apparatus in some experiments to measure the detectability of changes in spectral shape (profile analysis) at high frequencies.

Drs. Huanping Dai and Kourosh Saberi have collaborated on this project. We have measured with several earphone systems and have also made measurements in Dr. John Middlebrooks' free-field room. The results we have obtained are very puzzling.

One major application of the ability to discriminate changes in the power spectrum of the stimulus (profile analysis) is to localize sounds in space. The locus of points in the sagittal plane defines what has been called a 'cone of confusion,' because the interaural differences of time and intensity are nearly the same on this cone. Disambiguating different loci on this cone can be aided by the differential filtering of the head-related transfer function. The received spectrum of a wide-band source changes as we vary the position of the source in the sagittal plane, especially for frequencies above 6 kHz. Three experiments have been conducted to measure the ability of listeners to hear changes in spectral shape at these frequencies. The following is a progress report on these efforts.

The goal of the first experiment was to compare the listener's ability to discriminate spectral shape in different frequency regions. Three-tone spectra with medium bandwidths were varied in center frequency f_c from 250 to 16,000 Hz. For a given center frequency, the lower and higher frequencies were $f_c/1.38$ and $1.38 \cdot f_c$. Thus, all three components presumably fell into different critical bands. For the standard spectrum, all three components were equal in level. The median level of the standard complex was 60 dB SPL per component, and the overall level of the complex was chosen from a rectangular distribution with a 20-dB range. In the signal-plus-standard spectrum, the level of the center component was increased relative to the other two components by adding, in-phase, a component to the central component of the standard. The threshold for this added signal was determined in a two-alternative forced-choice task using an adaptive two-down one-up procedure whose equilibrium point is 70.7 % correct. The threshold values are reported in decibels as the ratio of the added signal to the standard component, 20 log ($\Delta p/p$).

Because of the problem of standing waves at the higher frequencies, the experiments were conducted using three different sound transducers: (1) a conventional headphone (Sennheiser Headphone, HD-450), (2) an insert earphone (Etymotic ER-2), and (3) a sound delivered through a long (5 meter) lossy plastic tube with a diameter of about 1 cm. The subjects listened binaurally with the phones in-phase for the conventional headphone. For the other conditions, the listening was monaural. The long lossy tube provides a nearly perfect impedance match at the entrance of the ear canal, and, by decreasing reflections at this point, minimizes changes in pressure level as a function of frequency at the eardrum (Zhou and Green, 1994). For some of the higher frequency conditions, some nonlinear distortion products were audible. Thus for f_c > 5 kHz, a lowpass noise band was used extending below 4 kHz and having a spectrum level of 24 dB.

Figure 2 shows the mean results obtained with three normal-hearing subjects. The signal-to-standard ratio at threshold is plotted as a function of the center frequency f_c. The circles represent the thresholds obtained with the conventional headphones, the triangles with the insert phone, and the squares with the long tube (two subjects). The results obtained with the three transducers are nearly the same. Profile discrimination of the three-tone complex deteriorates markedly once the center frequency is above about 5000 Hz. When the signal level is very large, it is possible that the discrimination is based on differences in overall level measured successively in the two intervals. In that case, the level of the signal-plus-standard spectrum will reliably exceed the

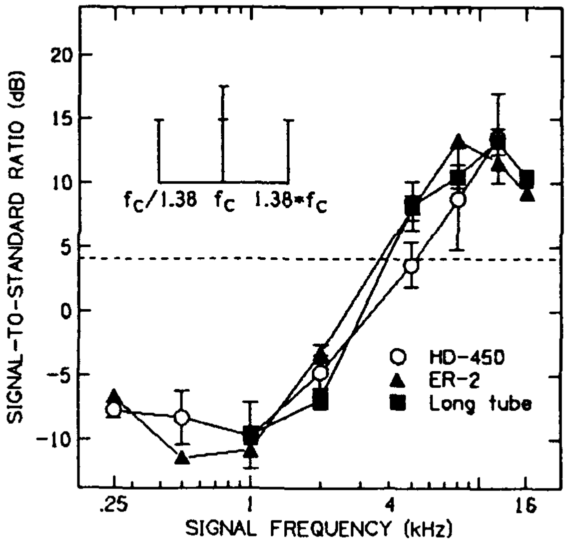

Figure 1. Profile discrimination for a 3-tone complex.

level of the standard spectrum, despite the 20-dB randomization of presentation level. The dotted line shows the threshold value achievable for an ideal detector listening to only changes in overall level during the two intervals of the forced-choice task. Many of the measured thresholds exceed this level. We interpret this to mean that the listeners continued to listen for the simultaneous changes in spectral shape even when the successive differences between overall level provided a potentially stronger cue. No attempt was made to instruct the observers to listen to the successive changes in overall level.

Two more experiments were conducted in the free field, which provides an experimental setting very similar to that used to study sound localization. In the first free-field experiment, we used a stimulus similar to that used in the headphone experiment, except that the number of components was increased from three to seven. The seven components were spaced in frequency at equal intervals on a logarithmic scale extending from 2327 to 16,000 Hz. Each of the seven components was set at a constant sensation level based on absolute threshold measurements for each individual listener. The median sensation level of the entire complex was about 60 dB, and the overall level was randomly varied ± 5 dB about that level.

Figure 3 presents data for this experiment. Each symbol represents data for a single listener. The dotted line again represents the performance possible for an ideal observer listening only to successive changes in absolute level. The observed thresholds nearly always exceed these levels. These data are similar to those obtained in the earlier headphone experiments. The general result is that listeners are not able to hear changes in the spectral shape of a multiple component complex at the higher frequencies. In the speech range, listeners can hear 1-dB changes in the intensity of a single component of a seven-component complex. At the higher frequencies, a change of over 20 dB is needed in some cases for the same detection accuracy.

In the second free-field experiment, a very different stimulus was used to measure the ability to hear changes in spectral shape--what we call a rippled-noise stimulus. A nearly continuous spectrum was employed that sounded noise-like rather than tonal. The standard spectrum contained many equal-amplitude components spaced in frequency 6.25 Hz apart (the reciprocal of the duration). The phase of each component was randomized for each presentation. The components extended in frequency over the range from 8 to 16 kHz. The change in spectral shape was created by imposing a sinusoidal ripple on that flat spectrum. The ripple was sinusoidal on a logarithmic frequency scale. The phase of the ripple was randomized on each presentation to discourage detection based on the absolute level of the spectrum in any frequency region. The size of the ripple was adjusted adaptively in a three-down one-up forced-choice procedure, which produces an equilibrium point of 79.4% correct. We can think of the signal-plus-standard spectrum

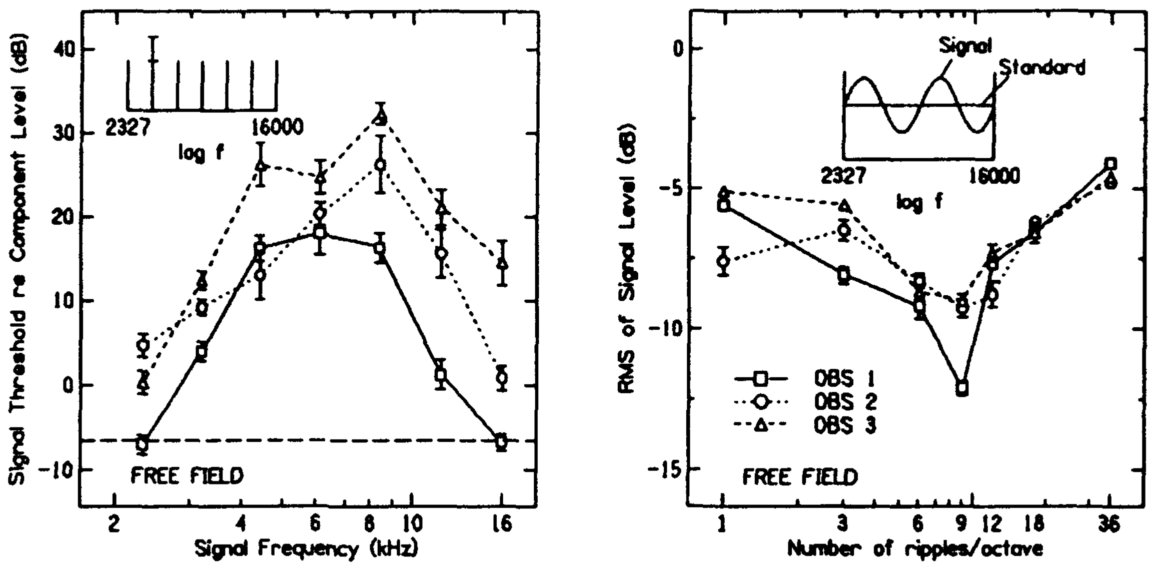

Figure 2. Profile discrimination at different frequencies of a 7-tone complex (left panel). Profile discrimination with ripple noise at different ripple frequencies (right panel).

as the addition of a set of 'signal' components to the standard spectrum. Each 'signal' component is either in- or out-of-phase with the corresponding component in the standard spectrum, thus producing an increase or decrease in the level at that frequency. The threshold can be expressed as the rms of this 'signal' compared to the rms level of the standard components. The loudspeaker was digitally equalized to produce a standard having a flat amplitude spectrum, as measured with a sound level meter (Bruel and Kjaer Model 1613) located at the position of the listener in the sound-attenuated chamber.

Figure 4 shows discriminability data for this rippled-noise stimulus. The ordinate is the threshold rms signal-to-standard ratio in decibels. The abscissa is the number of ripples per octave. All three listeners were able to discriminate changes in the spectral shape of this noise-like stimulus. The listeners reported hearing a difference in the quality of the noise similar to that heard with noise that is time delayed and added to itself (comb filtering). The best detection occurred with about nine ripples per octave. These results are similar to those obtained for similar stimuli at the lower frequencies, except that those studies found that the best detection occurred with about three ripples per octave (Hillier, 1991; Green, 1993). Also, the lowest threshold value was about -23 dB, at least for wide-band spectra, 100-6400 Hz.

These results of the rippled-noise experiment are quite unlike the results obtained with the three- or seven-component complexes. For multitonal complexes, 30-dB changes in the level of individual components were sometimes inaudible. The reason for these differences in sensitivity changes in spectral shape at the high frequencies is not understood, and further experiments are planned to probe these very different findings.

Temporal Factors in Profile Analysis.

The final topic where we believe further research is warranted concerns the effects of temporal factors on the discrimination of changes in spectral shape. In a recent paper (Dai and Green 1993--see reference 2 above), we measured how changes in total stimulus duration affected the ability to hear changes in the power spectrum of multicomponent complexes. We found that the effects of duration differed depending on the number of components in the complex and the frequency spacing of the components. At very short duration, the threshold for the signal increased markedly for narrow frequency spacing. The results are consistent with the idea that the width of the auditory filter changes over time. For sound as short as 10 msec, the effective range of spectral integration was five times wider than the range for sounds of 100 msec duration.

The idea that the critical band has a varying bandwidth was suggested earlier in experiments involving forward masking (overshoot), but has not been widely accepted. Indeed, the physiological evidence suggests that the width of the filter is determined by structural constraints and is therefore constant. Why then does the threshold for short duration signals increase so much for sinusoidal complexes? One experiment we would like to conduct involves measuring the detection of rippled noise at various durations. As our results with high-frequency spectra show, rippled noise sometimes produces results very unlike those obtained with multicomponent complexes.

The duration experiments and the experiment by Zera and Green on synchrony detection (references 3,4, and 5) bring to mind the earlier experiments by Green and Dai (1992, "Auditory Physiology and Perception", Eds. Y. Cazals, L. Demany, K. Horner, Pergamon Press) concerning the temporal relation between the signal and nonsignal components. The detection task involved a 21-component complex--equal logarithmic frequency spacing 200-5000 Hz and a duration of 500 ms. The standard spectrum had all the components at the same level. The signal consisted of an increment in level to the central (1000 Hz) component of the complex. If all components were temporally synchronous (all began and ended at the same time), the threshold (signal-to-standard ratio) was about -15 dB. Thus, the listener could just detect a 1-dB increase in the level of the 1000-Hz component. If the nontarget components began 25 ms before the 1000-Hz component, the threshold increased about 20 dB. Thus, the listener could just detect an 8-dB increase in the level of the 1000-Hz component. Synchrony between the target and nontarget components is a very important feature of profile analysis. We still do not understand why this is so critical and why it has such a profound influence on the measured thresholds.

We feel that more research should be devoted to this topic. Not only is this research needed to understand the basic stimulus variables in more detail, but it is needed in order to apply this research to real-world situations. In most realistic situations, the change in the auditory spectrum occurs at different times and with different degrees of synchrony among the components of the complex.